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Deep Currents in the Northwest Pacific Off Japan During KERE

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Deep-water measurements were obtained from a closely spaced hydrographic section that crossed the Japan Trench and the Kuroshio in the vicinity of the Kashima 1 Seamount. Vertical sections of temperature, salinity, density, oxygen, and nutrients are discussed for water below 1000 m. Hydrographic properties are perturbed in the vicinity of the seamount. Contrasting variabilities are found in the deep-water characteristics northwest and southeast of the seamount. Geostrophic calculations and properties suggest a mean deep-northward flow greater than 3 cm/s between 3000 m and 5800 m just east of the seamount. At the northwestern extreme of the section the existence of a southward-flowing Deep Western Boundary Current is suggested by silica distributions, as well as the dynamical properties.

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DEEP CURRENTS IN THE NORTHWEST PACIFIC OFF JAPAN DURING KERE

Introduction

The North Atlantic Deep Western Boundary Current (DWBC) is an important component of that ocean's thermohaline circulation (e.g., Hogg 1983). The model of Stommel and Arons (1960) suggests that a North Pacific DWBC should also exist, but that near Japan it could be northward or southward flowing depending on model parameters. We present closely spaced hydrographic sections at the western boundary of the North Pacific off Japan. These sections were obtained as part of the Kuroshio Extension Regional Experiment (KERE) (Mitchell 1990). In this report we emphasize the hydrography of the deep and bottom waters of the sections. A companion report (Teague et al. 1993a) describes the dynamics in the upper water column associated with the Kuroshio.

A major objective of the hydrographic component of KERE was to use chemical tracers to examine deep flows in this region with particular emphasis on the DWBC. Since there is no evidence for formation of deep water in the North Pacific (Reid 1973), any deep currents coming from the north should transport waters that are older (in the sense of surface ventilation) than surrounding waters. Likewise, a deep current from the south should transport younger waters. Since nutrient content increases and oxygen content decreases with the age of a water mass, the distributions of these chemicals provide a key for interpreting deep-water movements. Silica is particularly useful in the North Pacific because of the dissolution of opaline bottom sediments (Edmond et al. 1979).

Data

A northwest to southeast section of 18 closely spaced conductivity, temperature, and depth (CTD) /hydrographic stations (henceforth referred to as the KERE section) was occupied from 8 to 23 July 1992 on a line extending from about 37°N, 142°E to 33°N, 144°E (Fig. 1). The section begins on the slope just east of Honshu in about 1000 m of water. Since Japan is an island arc, this slope is properly referred to as the forearc slope, rather than the continental slope. The section trends southeastward across the Japan Trench. The trench is deeper than 7000 m; however, this section crosses the Kashima 1 Seamount, which rises to about 3600 m depth and which Kawai (1972) reports as forming a sill between the Japan Trench and the Izu-Ogasawara Trench to the south. Additionally, the section crosses an abyssal hill of about 4800 m depth. The hill, which is either missing or displaced in the ETOPO 5 (NOAA 1986) bathymetry (Fig. 1), lies about 40 km west of the Takuyo 2 and 3 Seamounts (34°N, 144°E), which rise to about 1500 m depth in an otherwise fairly flat basin of approximately 5500 m in depth. The differences in the measured depths along the KERE section from charted depths emphasizes that dependence on historical bathymetric databases for analyses can often be misleading. Station spacing telescopes from about 15 k: at the landward (i.e., NW) end of the section to about 50 km on the seaward (i.e., SE) (Each station includes silica, oxygen, nitrate, and phosphate measurements at standard i- ls in addition to the temperature and salinity measurements. Samples were collected to within 100 m of the bottom for most of the stations. Data collection and processing are described in Teague et al. (1993a, b). The Kuroshio Front is located at about 35.8°N, between Stations 9 and 10 (in the vicinity of the seamount).

Vertical Sections

Potential Temperature, Salinity, and Potential Density

Potential temperature, salinity, and potential density are shown in Figures 2-4. The upper 1000 m of the water column (described in detail in Teague et al. 1993a) predominately reflects the presence of the Kuroshio and its interactions with cold, fresh subarctic water. The Kuroshio Front is located near Station 10. On the onshore side of the front, an intrusion of cool, fresh Oyashio water is seen at Station 8. Offshore of the front, Subtropical Mode Water (SMW) is seen in the 17°C thermostad. Beneath the SMW is the salinity minimum, which characterizes the North Pacific Intermediate Water (NPIW).

At intermediate depths near the western boundary there are two interesting features. Isotherms and isohalines diverge slightly around 1500 m depth as they intersect the forearc slope at Station 2. Additionally, at Station 5 there is a slight divergence of isopleths over about 1 km of the water column and centered near 1500 m depth. Geostrophic velocity calculations indicate significant velocity shear associated with these two boundary features. When referenced to a near-bottom level of no motion, there is a 4 cm/s southwestward flow between Stations 2 and 3 centered at 1600 m. Near Station 5, there is a 2 cm/s northwestward flow embedded in southwestward flow of several centimeters per second and extending over the 1100 to 2300 m depth range. The bottom reference level is questionable for these near-bottom currents; choosing a level of no motion above these two features does not change velocity shears but may change directions.

In the deep waters of the section, isotherms slope very slightly downward away from Japan. The Kashima 1 Seamount perturbs this simple picture in two ways. First, immediately above the seamount there is an evident dip in the isotherms, which can be traced as far as 1500 m above the seamount. Also, the deepest isotherms are about 500 m shallower on the shelf side of the seamount. Another perturbation in the deep waters is evident above the abyssal hill where the 1.2°C isotherm bends upwards slightly.

Beneath the NPIW, salinity increases monotonically with depth. Near-bottom salinities are 34.695 psu, which is in close agreement with deep salinities reported by Mantyla and Reid (1983). In general, the deepest isohalines follow the bathymetry. However, as with potential temperature, the isohalines dip down directly over the seamount. The abyssal hill seems to have little effect on the isohalines.

The bending of the deep isopycnals across the seamount is indicative of geostrophic flow. Figure 5 shows a velocity profile computed from the two stations southeast of the seamount using 5800 m as a reference level. High surface water velocities of the Kuroshio are evident. In the deep waters, a relative velocity change of 8 cm/s is observed between 3000 m and 5800 m.

Potential temperature-salinity (TS) diagrams for the coldest waters (Fig. 6a) suggest only slight curvature in the relationship between 1.1 and 1.25°C. Below 1.1°C there is a deviation in the TS plot, with temperatures being slightly higher than expected from the trend in the waters just above. The deepest sample obtained in the Japan Trench (6100 m) had the highest near-bottom salinity (34.705 psu) and the coldest potential temperature (1.06°C) in the section.

Oxygen

Oxygen is generally close to saturation in the surface waters and concentrations rapidly decrease in the thermocline (Fig. 7). The oxygen minimum is found beneath the core of NPIW with the lowest oxygen values found at Stations 1 and 5. Beneath the oxygen minimum, the oxygen section is comparatively featureless. The deepest isopleths are slightly elevated northwest of the seamount, as is the case for temperature and salinity. The highest deep-water oxygen of 167 μmol/kg was found in our deepest sample in the Japan Trench. This is similar to the highest deep-water values observed by Talley et al. (1991) in the Kuril-Kamchatka Trench at 42°N and 48°N and by Roemmich et al. (1991) in the Bonin Trench at 24°N. Both of these trenches connect with the Japan Trench.

The θ-oxygen plot for the coldest waters reveals two slight changes in the bottom water relationships (Fig. 6b). There is a slight decrease in the slope of this plot near 1.4°C and again below 1.1°C.

Nutrients

The nutrients show their typical surface depletion and deep regeneration. For nitrate (Fig. 8) and phosphate (Fig. 9) this regeneration is associated with the oxygen minimum and leads to distinct mid-depth maximums. For silica (Fig. 10), the regeneration is largely associated with opaline sediment dissolution (Edmond et al. 1979). Sources of silica in the North Pacific are discussed in detail in Edmond et al. (1979) and Talley and Joyce (1992).

The silica maximum occurs between σ_θ of 27.6 and 27.7, or typically 2000 m. The highest silica concentrations are observed at Station 5 where the 170 μmol/kg contour encompasses nearly 1000 m of the deep water column. There is also evident bending upward of the isopleths at depths as shallow as 700 m at this station. Talley et al. (1991), in their sections at the western boundary near 42°N and 47°N, also reported narrow bands of slightly high silica in the 1500 to 2000 m depth range.

In the vicinity of the Kashima 1 Seamount, silica isopleths show a distinct pattern of higher silica above the seamount and lower silica at the surrounding stations. This pattern is evident in isopleths more than 2 km above the seamount.

Lowest deep-water silica is found in the trench. The deepest samples in this profile have concentrations less than 145 μmol/kg. Talley et al. (1991) also report low silica in the trench in their sections with trench silica concentrations increasing northward. Our values in the Japan Trench fit in with this pattern. However, in the Bonin Trench to the south, Roemmich et al. (1991) shows no particular effect on silica, though the trench values are similar to or slightly lower than those from the KERE section in the Japan Trench.

The deep nitrate and phosphate sections show less detail than silica due to data loss and analytical problems with phosphate (Teague et al. 1993b). In general, these data are compatible with other nearby nutrient sections (e.g., Talley et al. 1991; Kenyon 1983). Nitrate to phosphate ratios for the deep water are typically 14.5. The overall lack of features in the deep nitrate and phosphate sections (as well as oxygen) is reminiscent of the observation of Warren and Owens (1988) in the deep subarctic Pacific that these properties could be calculated to observational accuracy from potential temperature (excepting minor features).

Discussion

Deep and Abyssal Flow in the KERE Section

The KERE section indicates the presence of important deep and abyssal currents in this region. In the intermediate depth range at Station 5, the silica distribution and dynamic properties indicate a narrow, southward current. The width of the current is of the order of the station spacing ($\approx$30 km) and the effect on the isopleths is seen from 700 m to the bottom. The southward direction of the current is indicated by the silica enrichment. Additionally, the low oxygen minimum values at this station are consistent with a northern source for these waters, though the effect is slight and could be the result of enhanced oxygen consumption along the forearc slope. These observations are consistent with earlier work in this area utilizing dynamic calculations and neutrally buoyant floats (Nan'niti and Akamatsu 1966; Worthington and Kawai 1972) and with more recent hydrographic and current meter data obtained to the north (see next section).

Another deep current may exist next to the forearc slope at Stations 2 and 3 where isopleths diverge. The relative velocity change between 1500 and 2100 m was 4 cm/s. In this depth range at Station 2, nitrate is 5 to 9% lower than at similar potential temperatures at nearby stations. The effect on only nitrate suggests this chemical signal may result from denitrification associated with forearc slope sediments, though it is surprising that this is not observed more directly in the oxygen minimum. With this limited evidence, we cannot conclude whether this feature is part of the long-term circulation or a time-dependent feature.

In the bottom waters in the vicinity of the trench, the slope of the isopycnals indicates a significant abyssal current with a scale width of 100 km. Assuming a bottom reference, a northward flow is indicated. This is consistent with the low silica concentrations and high oxygen content of these waters. This current, too, fits in with the picture established by recent hydrographic work to the north of the KERE study area as discussed in the next section.

There is an interesting aspect to the water movements associated with the trench in the KERE section. If Station 10 had not been occupied, isopleths for potential temperature, salinity, density, and silica would all bend upward over the seamount, as would be expected for uplift of water over an obstacle (e.g., Owens and Hogg 1980; Roden and Taft 1985). However, it is clear that immediately over the seamount (i.e., at Station 10), isopleths dip downward. Apparently this is related to the presence of the Kuroshio Front at this station. The interaction between the surface and deep flow at this station is seen both in the dip in the deep isopleths and in the doming of isotachs as shallow as 400 m (Teague et al. 1993a). This interaction may well be unique to this section since to the south the bottom flow is kept to the east of the Kuroshio by the Izu-Ogasawara Ridge. To the north the Kuroshio bends eastward away from the trench as it leaves the Japanese coast. Although we know of no other reports of this seamount-Kuroshio interaction, most reports do show the Kuroshio Front in this general vicinity. It appears that the Kuroshio is directed to this interaction by its usual constraint to flow through a 1200 m deep passage in the Izu-Ogasawara Ridge 400 km to the southwest of the seamount (e.g., White and McCreary 1976).

The deep potential temperature-salinity and temperature-oxygen relationships (Figs. 6a and b) suggest slight variations in deep- and bottom-water sources. The change in slope of the potential temperature-oxygen curve at $\approx 1.4°C$ corresponds to a depth of 3000 m. This appears to be the deepest level at which waters can be exchanged between the Shikoku Basin and the Northeast Pacific Basin. The other slope change below 1.1°C is likely related to geothermal heating (Joyce et al. 1986).

Deep and Abyssal Circulation in the Northwest Pacific

The KERE section adds to the increasingly rich picture of deep circulation in the Northwest Pacific. Along the northern boundary is a topographically constrained eastward geostrophic flow above the Aleutian Rise and Trench (Warren and Owens 1985; 1988; Reed 1969). This flow can be traced on a map of potential temperature at 4000 m back to a northward current between the Zenkevitch Rise and the Kuril-Kamchatka Trench (Warren and Owens 1988). Sections across this trench at 42°N and 47°N likewise indicate northward flow below 4500 m (Talley et al. 1991). Further to the south the KERE section continues this picture of a northward abyssal current which becomes constrained into an eastward jet at the northern boundary. Even further to the south at 24°N, sections across the Bonin Trench also indicate northward flow (Roemmich et al. 1991). It is interesting to note that from the Bonin Trench to the Aleutian Trench, there is little change in the oxygen, nitrate or phosphate content of these abyssal waters. Assuming the flow in or above these trenches is connected, this suggests that the rate of deep and benthic respiration associated with these waters is low compared to the rate of their ventilation through advection and mixing.

As was pointed out by Warren and Owens (1988), deep current meter data at 165°E (Schmitz 1987) suggests a broad westward flow through the Northwest Pacific Basin feeding the narrow abyssal boundary current. However, similar deep current meter records at 152°E (Schmitz et al. 1987) are more ambivalent regarding this flow direction. Also, there is some evidence of northward flow to the east of the Emperor Seamounts in the INDOPAC section (Kenyon 1978; 1983); though Roden and Taft (1985) found no similar effect in later more detailed sections across the seamount chain.

In addition to the abyssal northward current, there is increasing evidence of a mid-depth boundary current compatible with Stommel-Arons deep circulation theory. Warren and Owens (1985; 1988) describe deep-westward flow associated with the Alaskan Stream just to the north of the eastward jet and the Aleutian Trench. They interpreted this current with a modified Stommel-Arons model. After rounding the Emperor Seamount chain to the north, they indicate that this current flows southward becoming a deep western boundary current. Talley et al. (1991) provided further evidence of this current at 42°N and 47°N at the western boundary. Silica enrichments in this current are evident in the sections of Warren and Owens (1988) and Talley et al. (1991). The KERE section continues the trace of this current to the south, as evidenced by the silica and dynamic anomalies at Station 5. If this current continues southward, it must be deflected to the south-southeast by the Izu-Ogasawara Ridge 400 km beyond our section. Thus, the association of the southward DWBC with the Kuroshio probably occurs only in a limited range of latitudes near the KERE section.

Conclusions

The closely spaced KERE hydrographic section helps provide a more detailed understanding of the deep and abyssal circulation in the Northwest Pacific. Several conclusions can be drawn from this work:

a. A deep western boundary current is found at intermediate depth in this ocean basin. The current appears to begin in association with the west-flowing Alaskan Stream (Warren and Owens 1988), turn south around the Emperor Seamounts, and continue at least as far south as 36°N. South of this section, the current is likely to be topographically constrained by the Izu-Ogasawara Ridge.

b. A north-flowing abyssal current appears to flow from at least as far south as the Bonin Trench (Roemmich et al. 1991) and continue northward along the Japan Trench, the Kuril-Kamchatka Trench (Talley et al. 1991), and then form the eastward jet above the Aleutian Trench (Warren and Owens 1988).

c. There is a dynamic interaction between the Kashima 1 Seamount and the Kuroshio. The Kuroshio appears to depress isopleths over the seamount (presumably affecting the abyssal current); while the seamount results in a doming of the isotachs of the Kuroshio (Teague et al. 1993a).

We note that with a coarser station spacing this picture would not have emerged. The elimination of two stations from this section (5 and 10) would have obscured the observation of the deep western boundary current and the seamount-Kuroshio interaction. Further work is needed to quantify the hydrographic observations made here. Moored instrumentation and drifters deployed as part of the KERE program may provide this information.

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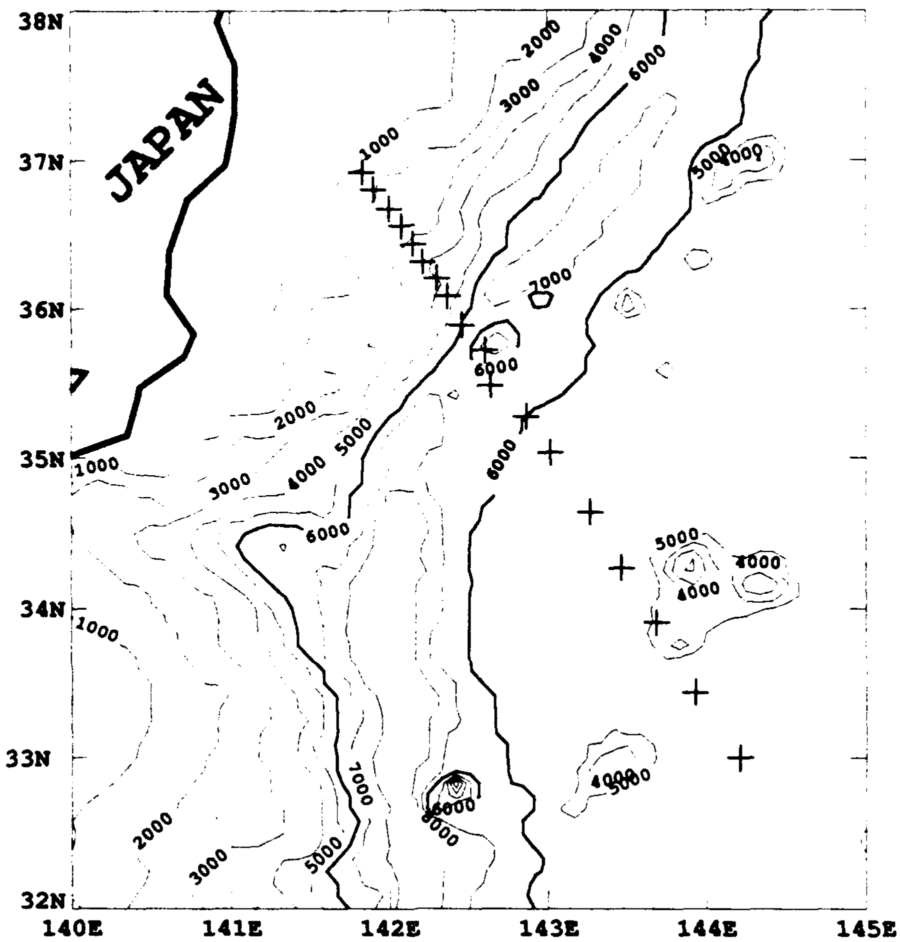

Figure 1. CTD/hydrographic-station locations are indicated by +s along the KERE section. The 6000 m contours (bold) indicate the boundaries of the Japan Trench. The Kashima 1 Seamount is located beneath the section at about 35.7°N. The Takuyo 2 and 3 Seamounts are located northeast of the section at about 34°N. Bathymetry is from ETOPO 5, a 5-minute latitude by 5-minute longitude worldwide gridded database (NOAA 1986) and generally reflects the actual depths measured when collecting these data.

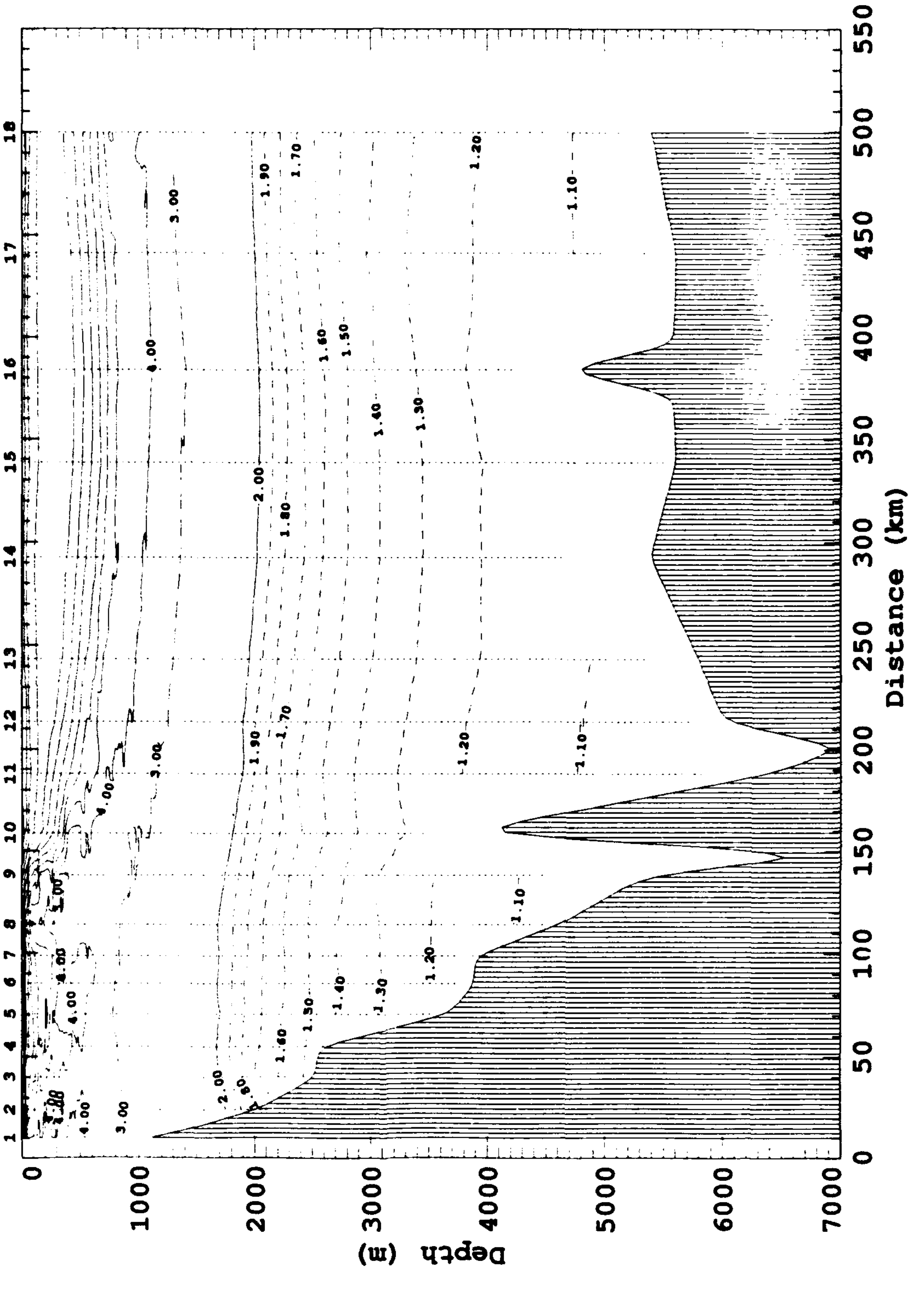

Figure 2. Vertical section of potential temperature (°C). Station numbers are at the top of the plot, and data extent is indicated by vertical dashed lines.

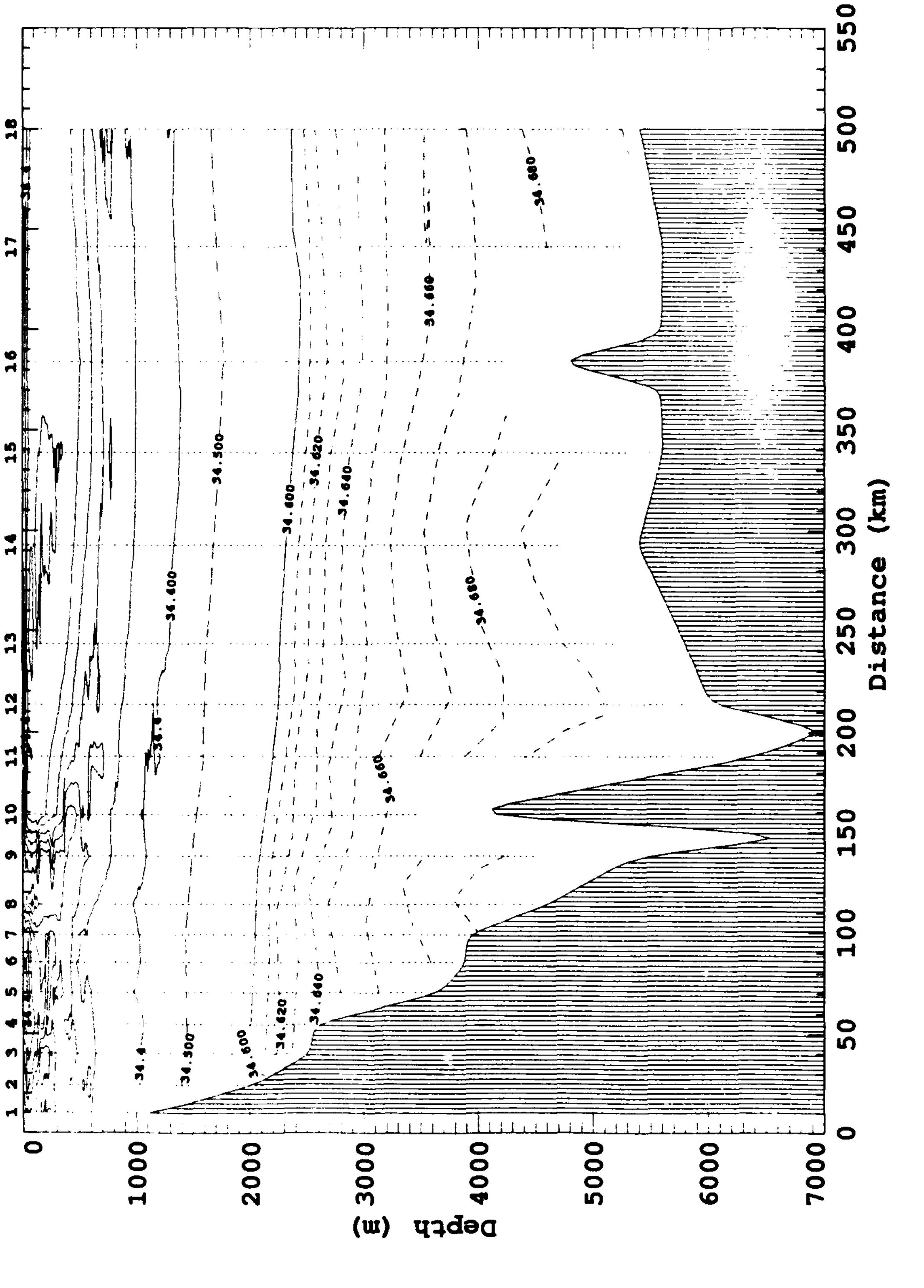

Figure 3. Vertical section of salinity (psu). Station numbers are at the top of the plot, and data extent is indicated by vertical dashed lines.

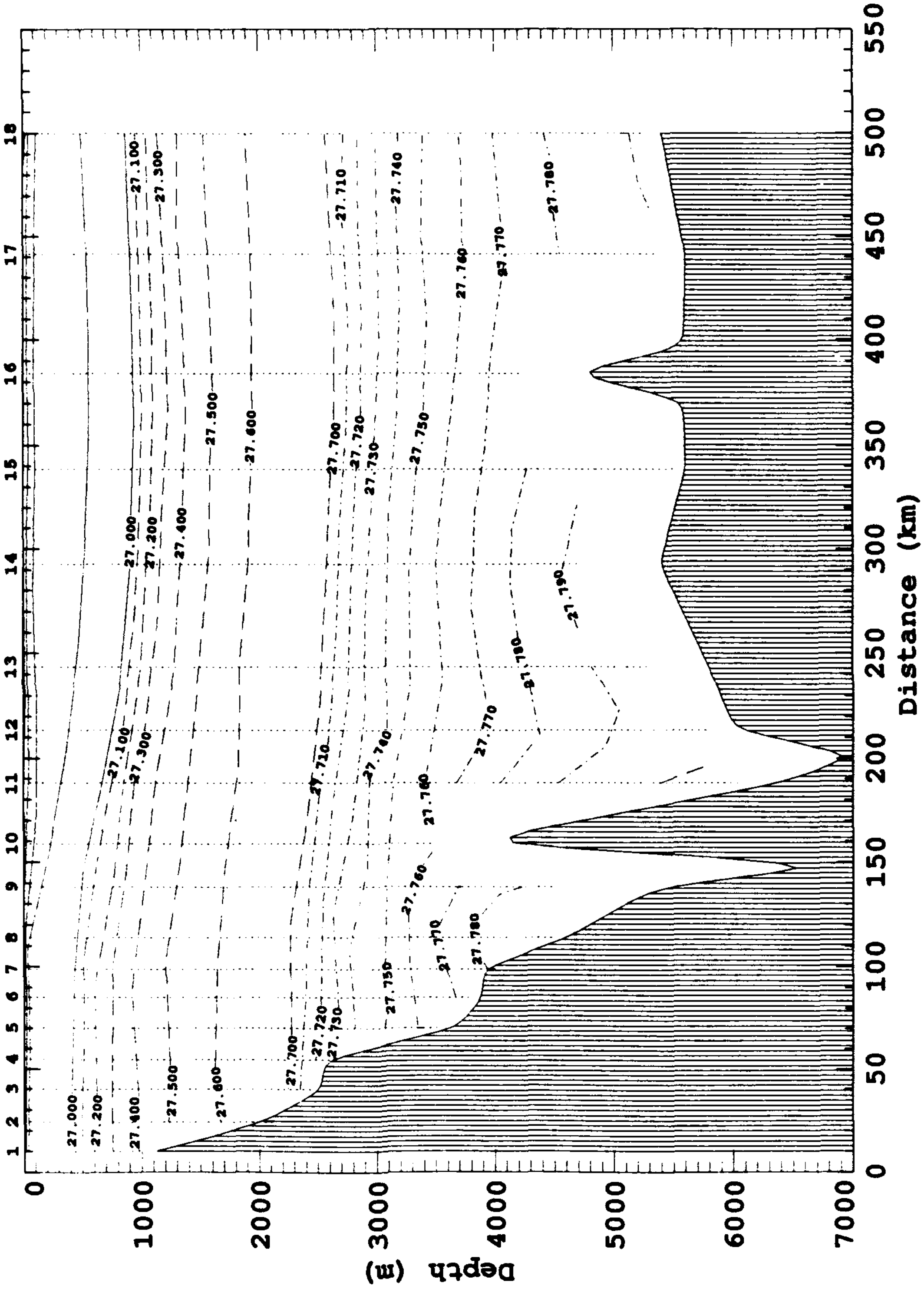

Figure 4. Vertical section of potential density (kg/m^3). Station numbers are at the top of the plot, and data extent is indicated by vertical dashed lines.

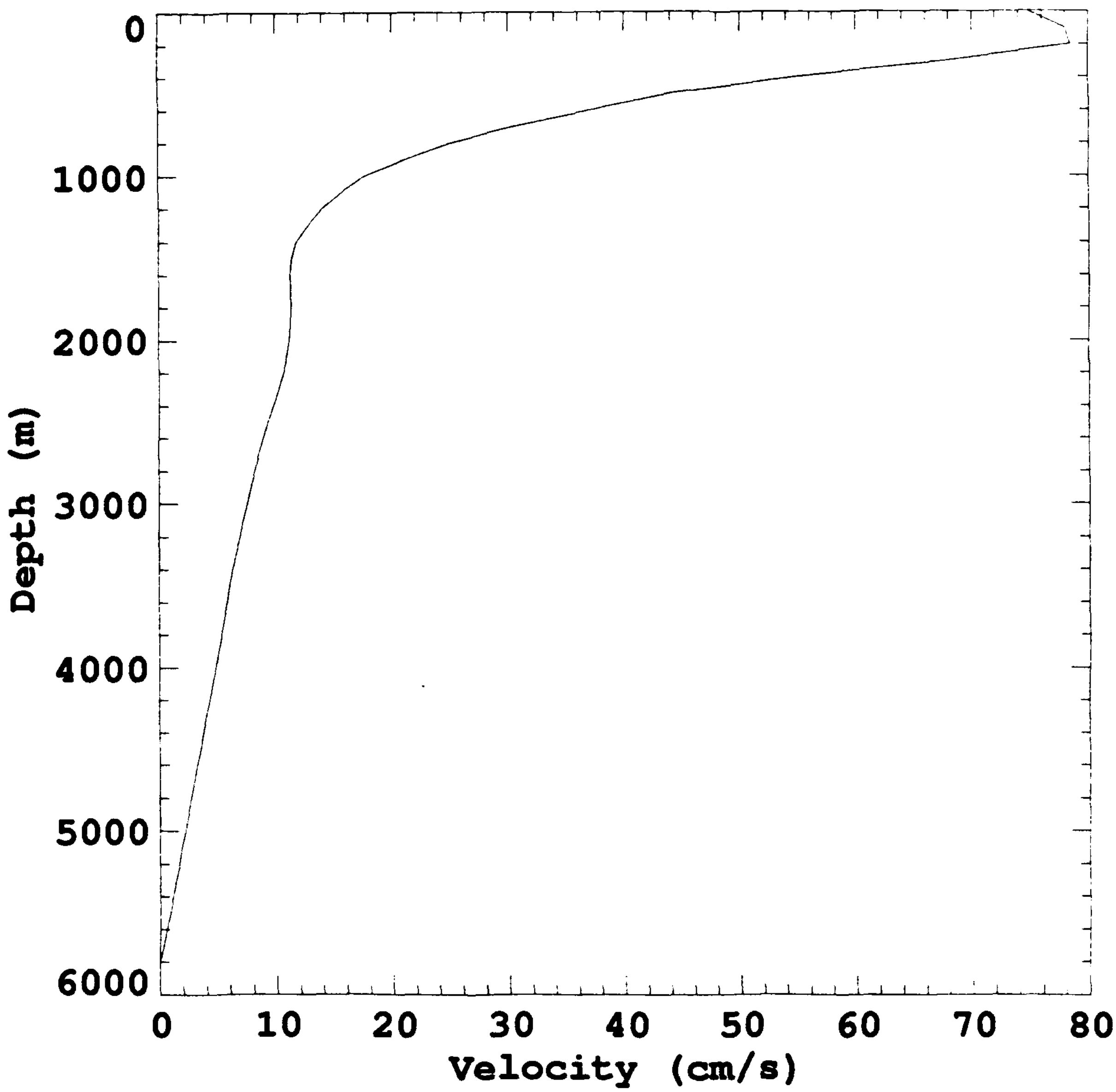

Figure 5. Geostrophic velocity profile between stations 11 and 12 using a level of no motion of 5800 m.

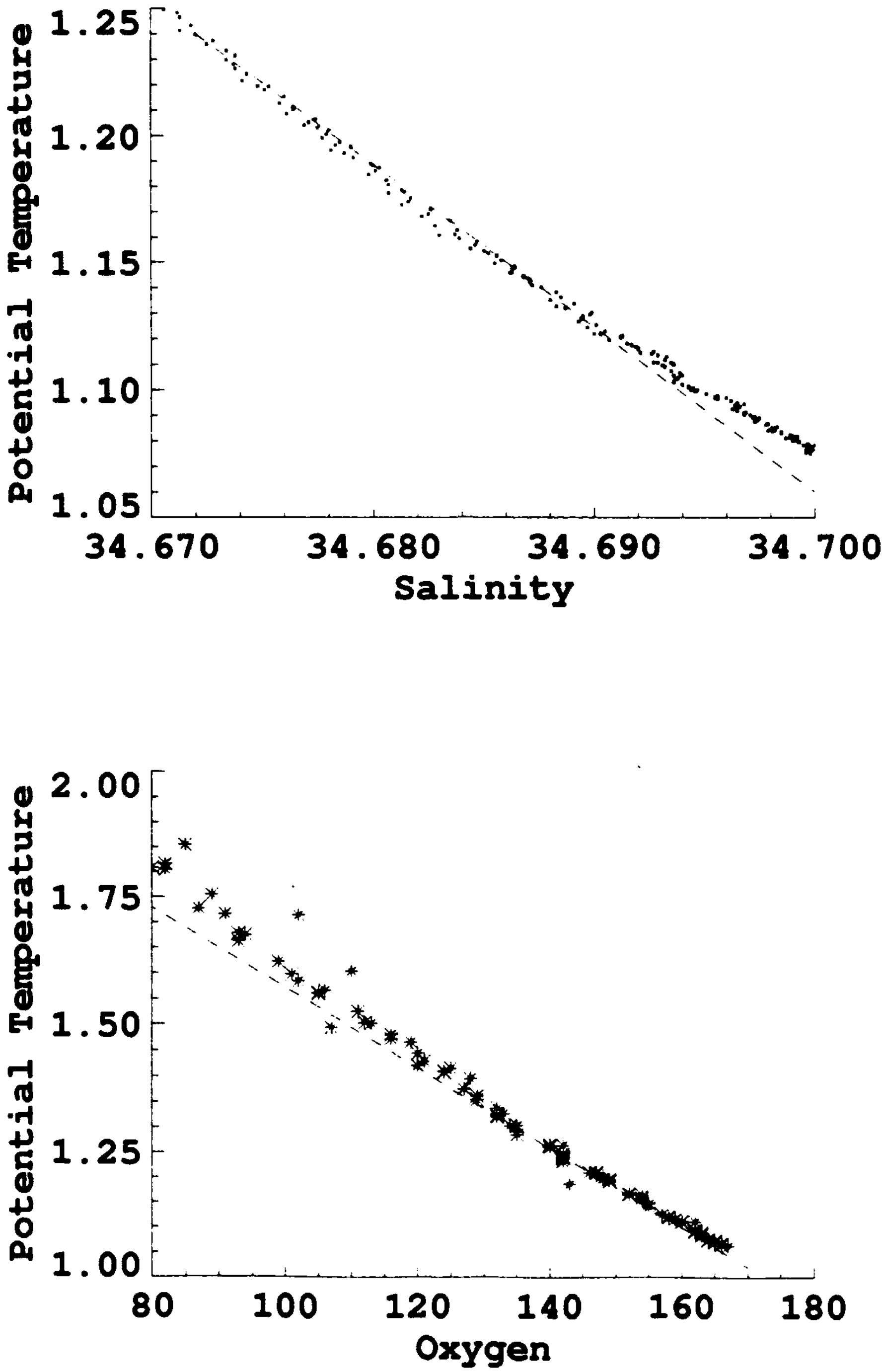

Figure 6. (a) Potential temperature vs. salinity for deep water at station 11. (b) Potential temperature vs. oxygen for deep water at Stations 11-18.

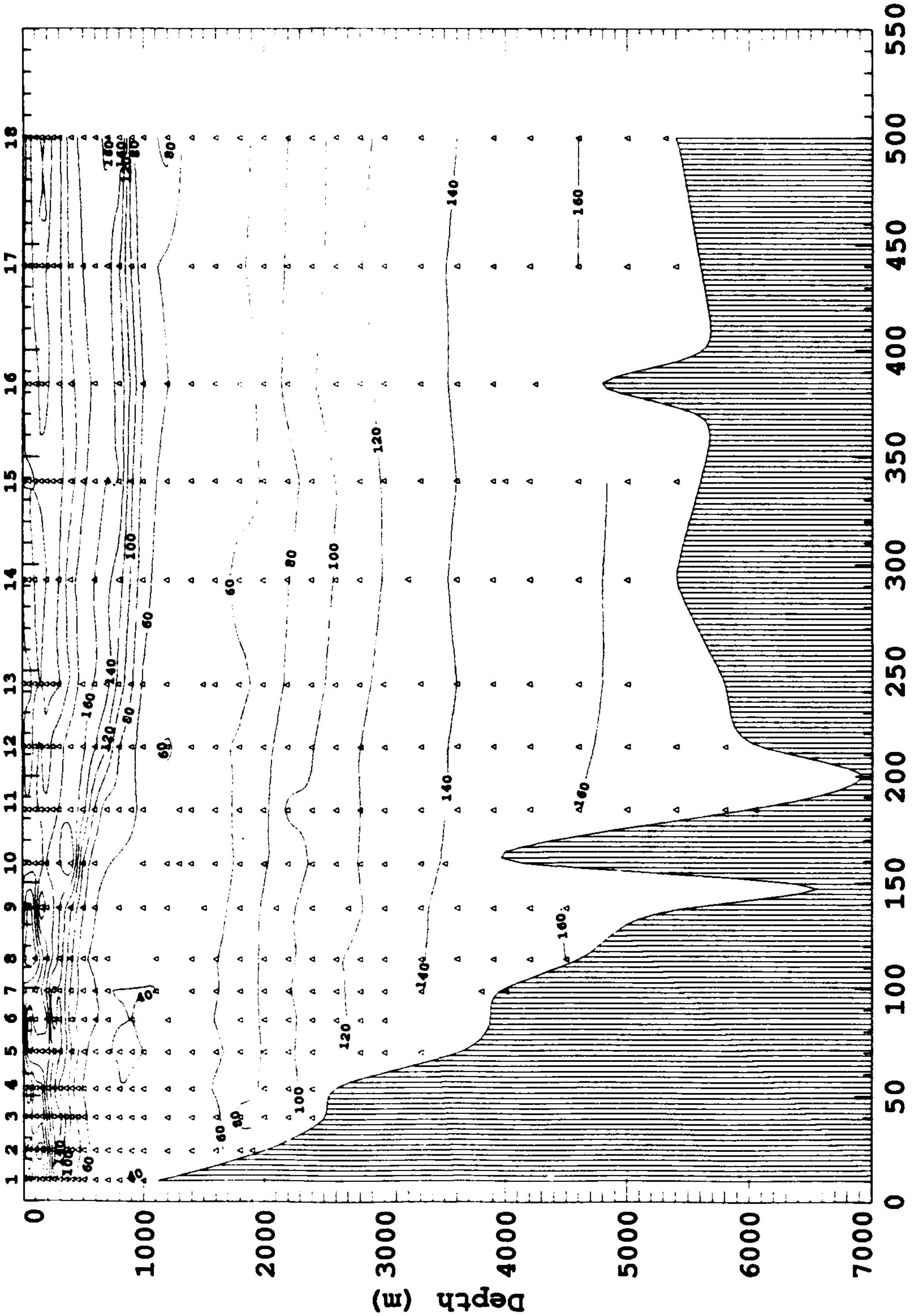

Figure 7. Vertical section of oxygen (μmol/kg). Station numbers are at the top of the plot, and data samples are indicated by triangles.

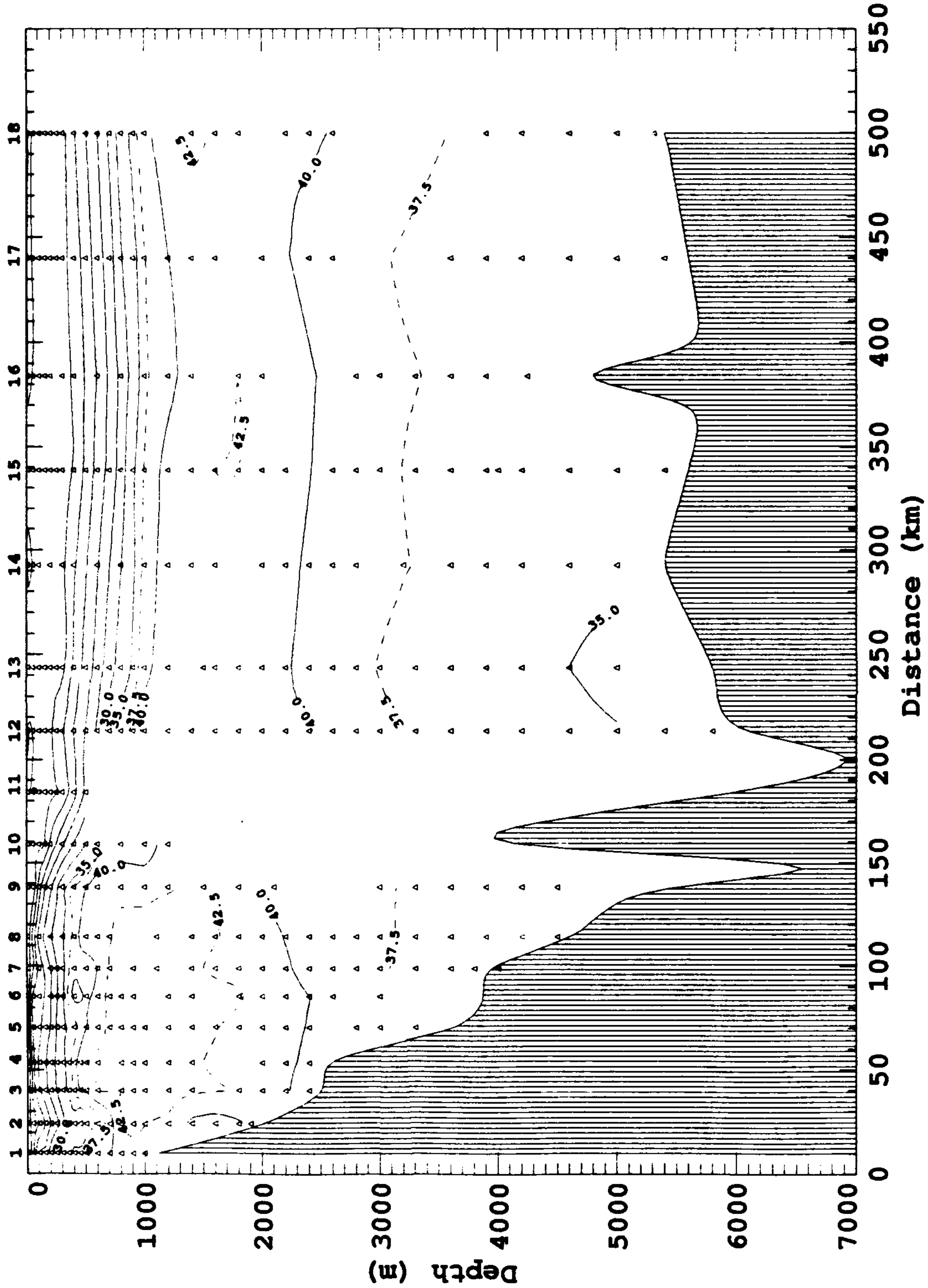

Figure 8. Vertical section of nitrate (μmol/kg). Station numbers are at the top of the plot, and data samples are indicated by triangles.

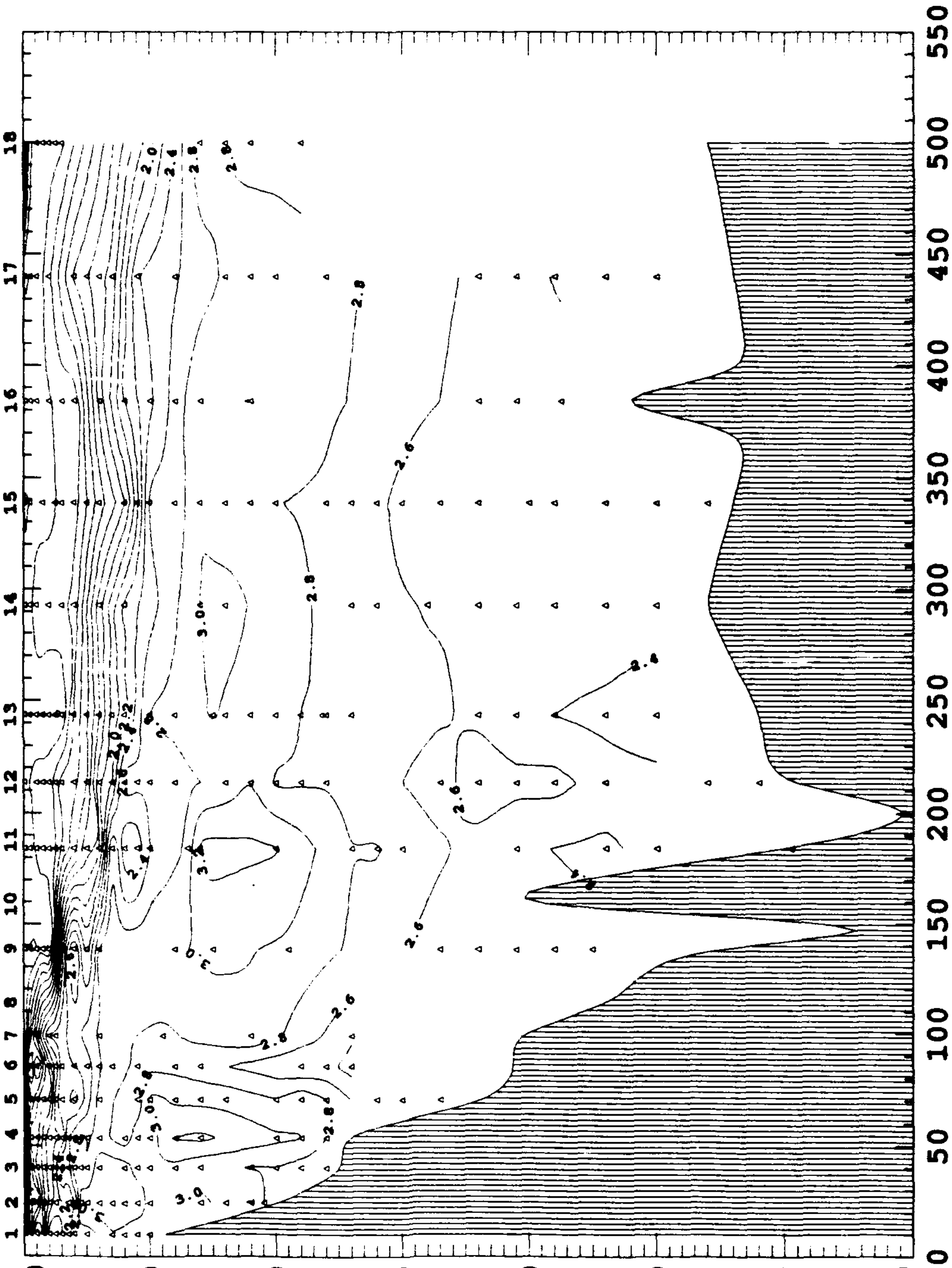

Figure 9. Vertical section of phosphate (μmol/kg). Station numbers are at the top of the plot, and data samples are indicated by triangles.

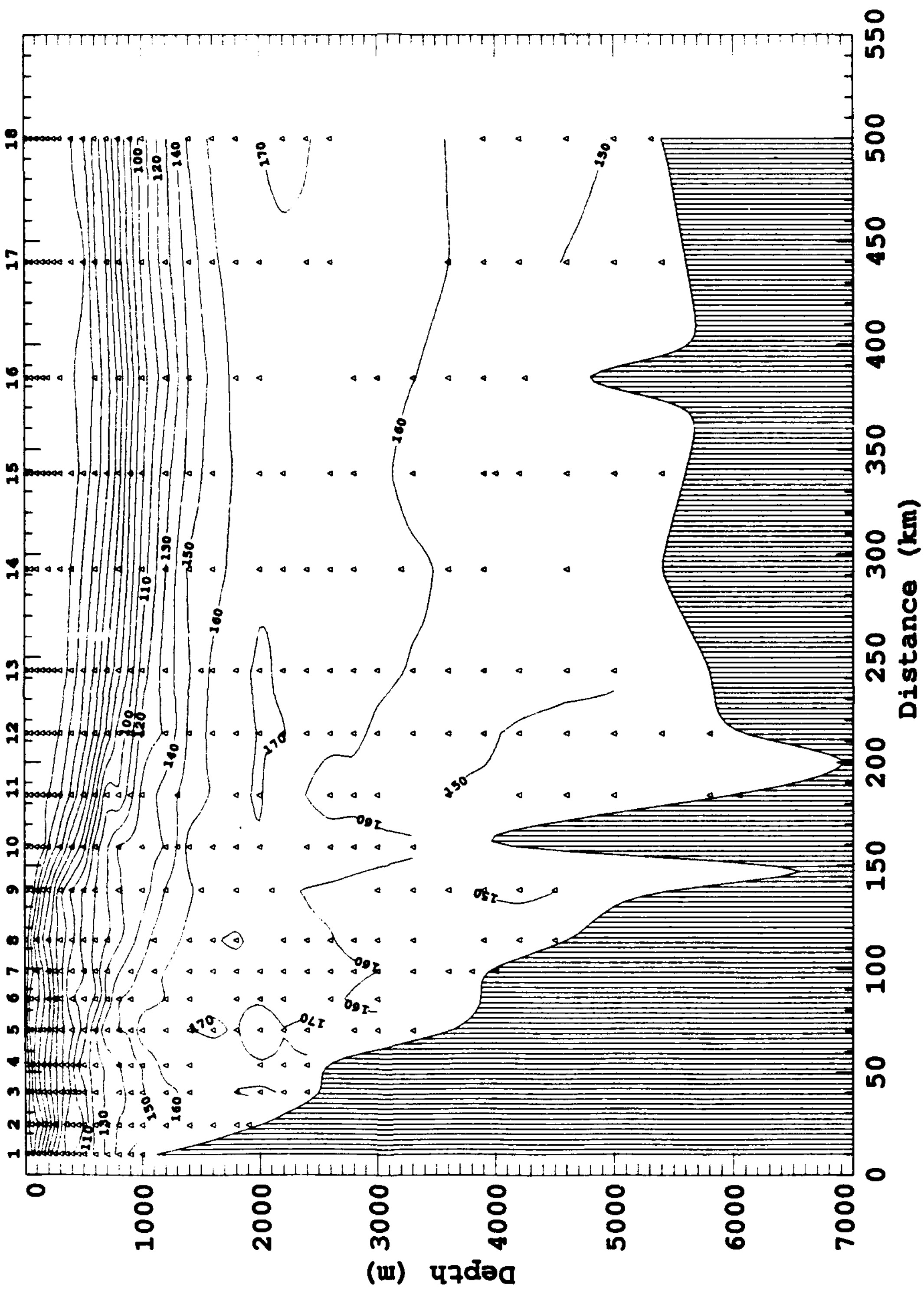

Figure 10. Vertical section of silica (μmol/kg). Station numbers are at the top of the plot, and data samples are indicated by triangles.